What is claimed is:

1. A method for detecting an open winding condition in a motor, the method comprising:

a. measuring a winding voltage , a winding current and a motor speed;

b. calculating a residue voltage for the winding, the residue voltage equaling the difference between a measured voltage drop across the winding and a calculated voltage drop for the winding, the voltage drop calculated for a non-open winding condition; and

c. comparing the residue voltage to a threshold value.

2. A method according to claim 1, further including:

d. signaling when the residue voltage exceeds the threshold value, to declare an open winding condition.

3. A method for detecting an open winding condition in a dual-stator redundant motor, the method comprising:

a. measuring a first stator winding voltage, a first stator winding current and the motor speed;

b. computing a first residue voltage for the first stator winding, the first residue voltage equaling the difference between a measured voltage drop across the first stator winding and a calculated voltage drop value for a non-open first stator winding ;

c. measuring a second stator voltage across a second stator winding and a second current through the second stator winding;

d. calculating a second residue voltage for the second stator winding, the second residue voltage equaling the difference between a measured voltage drop across the second stator winding and a calculated voltage drop value for a non-open second stator winding;

e. calculating a residue voltage difference equal to the magnitude of the difference between the first residue voltage and the second residue voltage; and

f. comparing the residue voltage difference to a threshold value.

4. A method according to claim 3, the method further including:

g. signaling when the residue voltage difference exceeds the threshold value, to declare an open winding condition .

5. A method according to claim 4, the method further including:

h. signaling when the first residue voltage exceeds a first residue threshold value to declare an open winding condition .

6. A method according to claim 3, the method further including compensating for measurement delay before calculating a residue voltage difference.

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APPENDIX A: SOURCES OF ERROR IN RESIDUE-BASED OPEN-WINDING DETECTION

Residue voltage equation:

theoretical: $r_q = V_{qLN} - K_{eLN}\omega_m - I_q R_{LN}$

computed: $r_q = \hat{\tilde{V}}_{qLN} - \hat{K}_{eLN}\hat{\omega}_m - \hat{I}_q \hat{R}_{LN}$, $\hat{\tilde{V}}_{qLN} = \hat{V}_{qLN} + \hat{K}_d \hat{V}_{dLN}\hat{\omega}_m$

Terminal voltage equations for 3-phase permanent magnet synchronous motor:

$$V_{qLN} = e_q + I_q R_{LN} + I_d \omega_e L_{LN} + L_{LN}\frac{dI_q}{dt}$$

$$V_{dLN} = e_d + I_d R_{LN} - I_q \omega_e L_{LN} + L_{LN}\frac{dI_d}{dt}$$

$$e_q = K_{eLN}\omega_m \cos\tilde{\theta}_e$$

$$e_d = K_{eLN}\omega_m \sin\tilde{\theta}_e$$

($\tilde{\theta}_e$ is error in estimate of electrical angle, normally 0)

Source of error	Approx. (small-signal) error in r_q	Significance (Δ: is this term reduced when comparing halves of a redundant motor?)			
		qualitative	typical quantitative	Δ	
$\tilde{K}_{eLN}$	$-\tilde{K}_{eLN}\omega_m$	Large	7% V_0	yes	Motor parameter tolerance $V_0 = \frac{V_{bus}}{\sqrt{3}} \approx$ full scale line-neutral voltage.
$\tilde{R}_{LN} = R_{LN} - \hat{R}_{LN}$ (actual - estimate)	$-I_q \tilde{R}_{LN}$	Possibly large	10% $I_q R_{LN}$	yes ($I_{qdm} \approx 0$[1])	Motor parameter tolerance
$\tilde{\omega}_m$	$(K_d V_{dLN} - K_{eLN})\tilde{\omega}_m$	negligible			Speed estimate error LPF makes only the DC component of $\tilde{\omega}_m$ significant; for any sensors used for commutation, this is 0.
$\tilde{I}_q$	$-\tilde{I}_q R_{LN}$	small to moderate	2-5% $I_q R_{LN}$		Current sensor tolerance
$\tilde{V}_{qLN}$	$\tilde{V}_{qLN}$	Moderate	2% V_0		Voltage sensor tolerance (resistor divider)
$I_d \neq 0$	$I_d \omega_e L_{LN}$	negligible			Current controller error: I_d is controlled to 0 with a PI loop, so when r_q is LPF, this term disappears

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[1] Assuming differential mode I_q between halves of a redundant motor is small, this term is reduced.

Source of error	Approx. (small-signal) error in r_q	Significance (Δ: is this term reduced when comparing halves of a redundant motor?)			
		qualitative	typical quantitative	Δ	
$\frac{dI_q}{dt} \neq 0$	$L_{LN}\frac{dI_q}{dt}$	very small	$2L_{LN}\frac{I_{qlim}}{\tau_{LPF}}$	yes ($I_{qdm}\approx 0$)	Changing current command: LPF makes this term small except for slow ramp rates from full regen to full motoring current (or vice-versa)
$\tilde{\theta}_e$	$K_{eLN}\omega_m(1-\cos\tilde{\theta}_e)$	small to moderate	$15° \to 3.4\%V_0$ $10° \to 1.5\%V_0$ $5° \to 0.4\%V_0$		Error in electrical angle estimate: LPF makes only the DC component of $\tilde{\theta}_e$ significant
$\tilde{K}_d$	$\tilde{K}_d V_{dLN}\omega_m$	Small	$10\% K_d V_{dLN}\omega_m$		Error in phase lag compensation due to filter time constant uncertainty. (R and C tolerances) $K_d\omega_m$ is a filter phase lag and should be under 0.25 radians, which would make this term about 2.5% V_{dLN}, which is significant only at high power levels

Example system: max $I_q = 35A$, $V_0 = 42V$ (72Vbus), $R_{LN} = 0.14$ ohm, $L_{LN} = 0.44mH$, $\tau_{LPF} =$ 0.1s, $K_d\omega_m \leq 0.2$ rad, $\omega_e \leq 1880$rad/s (300Hz)

$\tilde{R}_{LN}$: largest $I_q R_{LN} = 4.9V = 12\%$ V_0 (so in this case $\tilde{R}_{LN}$ and $\tilde{I}_q$ terms are small)

$\to$ effect of $\tilde{R}_{LN}$ is about 1.2% V_0 worst case

$\frac{dI_q}{dt} \neq 0$: largest LPF($L_{LN}\frac{dI_q}{dt}$) $= 2L_{LN}\frac{I_{qlim}}{\tau_{LPF}} = 0.31V = 0.7\%$ V_0

$\tilde{K}_d$: $V_{dLN} \approx -I_q\omega_e L_{LN} \leq 29V$

$10\% K_d V_{dLN}\omega_m \leq 0.1 \times 0.2 \times 29V = 0.58V = 1.4\%$ V_0

So the largest sources of error in LPF(r_q) are probably $\tilde{K}_{eLN}$ (7% V_0 at high speeds) and $\tilde{V}_{qLN}$

(2%), with $\tilde{R}_{LN}$, $\tilde{K}_d$, and $\tilde{\theta}_e$ in the 1% range and everything else under 1%. Comparing r_q

between redundant halves should greatly reduce the $\tilde{K}_{eLN}$ term.

APPENDIX B: FILTER LAG COMPENSATION

If we are sensing motor phase voltages using the method depicted in fig. 5A

and V_a, V_b, V_c are sensed after passing through a low-pass filter,

5    $H(s) = \dfrac{1}{1 + \tau s + (\text{higher order terms})}$, this will cause an error in the derived values V_d, V_q.

as shown in fig. 5B. The xy/abc transformations are linear and this model can be simplified

to the algorithm illustrated in fig. 5C.

This can be further simplified to the algorithm shown in fig. 5D,

where $\omega_e = \dfrac{d\theta e}{dt}$.

10   So that a filter acting in the stationary frame is equivalent to the same filter, frequency

shifted by the electrical frequency of the motor, in the synchronous frame.

One effect of this, is that at DC in the synchronous frame,

$$\hat{V}_q - j\hat{V}_d = H(j\omega_e) \cdot (V_q - jV_d)$$

$$\approx \frac{1}{1 + \tau \cdot (j\omega_e)} \cdot (V_q - jV_d) \qquad \text{(we can drop higher order terms if}$$

$(\omega_e)\tau \ll 1)$

15   This attenuates the V_{dq} vector slightly and rotates it slightly. We can compensate for

this effect:

$$\hat{\hat{V}}_q - j\hat{\hat{V}}_d = \left(\hat{V}_q - j\hat{V}_d\right) \cdot \left(1 + j\omega_e\tau\right) \approx V_q - jV_d$$

$$\hat{\hat{V}}_q = \hat{V}_q + \hat{V}_d \cdot \omega_e\tau = \hat{V}_q + \hat{V}_d \cdot K_d\omega_m$$

$$\hat{\hat{V}}_d = \hat{V}_d - \hat{V}_q \cdot \omega_e\tau = \hat{V}_d - \hat{V}_q \cdot K_d\omega_m$$

where $K_d = \dfrac{P}{2} \cdot \tau$ P = # of motor poles   and

where $\hat{\hat{V}}_q$, $\hat{\hat{V}}_d$ are compensated quantities,

while $\hat{V}_q$, $\hat{V}_d$ are derived from measurement.

For open winding detection, only the compensated voltage $\hat{\hat{V}}_q$ is needed, which is equal to $\hat{V}_q + \hat{V}_d \cdot K_d \omega_m$. Hence, this extra term "$K_d \cdot V_{dLN} \cdot \omega_m$" is incorporated into the equation for the voltage residue, r_q, to compensate for filter time delay.

Note τ is actually a relative time $\Delta\tau$; if we measure θ_e using a low-pass filter with time lag τ_o, and measure currents using a low-pass filter, also with time lag τ_o, but V_a, V_b, and V_c are using an LPF with time lag τ_V, then we should use $K_d = \dfrac{P}{2} \cdot (\tau_V - \tau_o)$ to calculate voltages that would correspond to the currents and phase angles, which have time delay τ_o and not calculate the actual voltages with no time delay.